INTERFEROMETER AND ITS
FABRICATION METHOD

This application is based on Patent Application
No. 2001-017943 filed January 26, 2001 in Japan, the
content of which is incorporated hereinto by reference.

5   BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

The present invention relates to an
10   interferometer and its fabrication method, which
enable planar optical waveguide circuits used in
optical communication field to adjust optical path
lengths (phases) independently in the transverse
electric (TE)polarization mode and transverse magnetic
15   (TM) polarization mode.

DESCRIPTION OF THE RELATED ART

Optical circuits employing single mode waveguides
20   formed on a substrate are characterized by high
integration and mass productivity, and hence they are
essential to construct economical optical network
nodes. In particular, optical circuits utilizing
silica-based waveguides with SiO_2 as the main
25   ingredient has favorable characteristics such as low
loss, superiority in an affinity for silica-based
optical fibers, and long-term stability. Thus, a

large variety of optical components typified by arrayed waveguide gratings are put to practical use, and are applied to commercial systems.

These optical components are fabricated by
5   combining a glass film deposition technique such as flame hydrolysis deposition (FHD) and chemical vapor deposition (CVD) with a microfabrication technique such as reactive ion etching (RIE). More specifically, a glass film is deposited on a substrate such as a
10 silicon wafer to form an lower-cladding, followed by depositing a core layer with a refractive index higher than that of the cladding layer. Then, a core pattern is formed by the microfabrication technique to form an optical circuit, followed by depositing a glass film
15 to form an over-cladding layer, thereby fabricating an optical circuit composed of embedded waveguides.

Usually, the FHD carries out annealing with high temperature to consolidate a glass film, and the CVD also performs annealing to increase the transparency
20 of a glass film. The high temperature process causes thermal stress in the glass film constituting the waveguides, resulting in waveguide birefringence (B-value) in which the effective refractive index of the waveguide varies depending on the polarization state,
25 thereby bringing about optical polarization dependency in the circuit characteristics. In addition, since the waveguide birefringence differs slightly in a

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wafer surface because of fabrication error, it is
necessary to trim the waveguide birefringence locally
for each optical circuit to achieve satisfactory
optical circuit characteristics.

5   As a conventional local waveguide birefringence
trimming technique, a method is proposed that utilizes
a stress-applying film consisting of an amorphous
silicon thin film (Japanese Patent Application Laying-
open No.1-77002 (1989). It exploits a phenomenon that

10   an amorphous silicon thin film, which is placed on a
waveguide, causes a strong tensile stress in the
waveguide, thereby varying the effective refractive
index of the waveguide through the photoelastic effect
of the glass. Varying the profile of the amorphous

15   silicon thin film enables the control of the stress
distribution, that is, the waveguide birefringence.
Besides, since the amorphous silicon thin film can be
removed by an Ar laser or the like, fine trimming of
the length of the amorphous silicon thin film in

20   accordance with the optical circuit characteristics
enables the effective refractive index of the
waveguide to be adjusted including the waveguide
birefringence.

The technique using the amorphous silicon stress-
25   applying film is more actively applied to a
constituent element of a polarization beam splitter
(PBS) (for example, see, 'Birefringence control of

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silica waveguides on Si and its application to a
polarization-beam splitter/switch", Journal of
Lightwave Technology, Vol. 12, No. 4, Apr. 1994).

The PBS comprises a Mach-Zehnder interferometer
5   (MZI), which includes two 3dB optical couplers (50%
optical couplers) consisting of silica-based
waveguides and two waveguide arms formed on a
substrate (silicon substrate), and on which three
types of amorphous silicon stress-applying films with
10   different width are placed.

One of the three types of the amorphous silicon
stress-applying films with different width is 50 μm
wide, and is provided to control the waveguide
birefringence principally. The remaining two types
15   are 90 μm and 100 μm wide, and are basically provided
to control the effective refractive index of the
waveguide polarization independently. The length of
the amorphous silicon stress-applying film is trimmed
by removing its part by an Ar laser, so that the
20   optical path length difference between the two
waveguide arms becomes zero for the transverse
magnetic polarization mode, and λ/2 for the transverse
electric polarization mode, where λ is the wavelength.
Thus, according to a known interference principle, the
25   transverse magnetic polarization mode of the light
entering the input port is guided to the cross port,
whereas the transverse electric polarization mode is

guided to the bar port. Thus, the MZI functions as a PBS.

The waveguide birefringence trimming technique utilizing the amorphous silicon stress-applying film, however, has a problem of complicating the device configuration and increasing its cost because of the final trimming using a laser and of the need for aligning the position of the laser irradiation at an accuracy of a few tens of micrometers.

On the other hand, a local-heat trimming method (see, Japanese Patent Application Laying-open No.3-267902 (1991), for example) is put into practice as a method of trimming the effective refractive index of a waveguide. This technique changes the effective refractive index of the waveguide permanently by annealing the waveguide at rather high power by using thin film heaters patterned on the waveguide, thereby trimming the optical path length (phase) of the optical circuit. Since the thin film heaters are formed by the microfabrication technique using a photomask, it is enough to flow current through the thin film heaters without the high accuracy alignment at the annealing. Thus, the trimming is carried out by a rather simple equipment, enabling its automatization rather easily. This method, however, is insufficient as a method of controlling the waveguide birefringence because the principle of the

effective refractive index change and the control of
the polarization dependency still remain to be
elucidated.

5   SUMMARY OF THE INVENTION

     The inventors of the present invention have
pursued intensive research to find that the principle
of the foregoing local-heat trimming method is that it
10   mainly changes the quality of the cladding between the
heaters and the core by the local annealing (heating),
and particularly the cladding immediately under the
heaters (in other words, the glass quality near the
top surface of the cladding), thereby causing a stress
15   to be applied on the waveguide. Then, we demonstrated
experimentally that the polarization dependency was
controllable substantially by changing the stress
distribution by adjusting the width w of the local
annealing (heating) region. More specifically, we
20   found that when the width of the local annealing
region was 1.4-2.6 times the distance d from the top
surface of the over-cladding to the core center, that
is, in a range of $\pm 30\%$ of w_o, where w_o was twice that
distance d, the effective refractive index changed
25   almost polarization independently, and that a local
annealing region wider than w_o made the transverse
magnetic polarization mode more dominant in the

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refractive index change, whereas a local annealing
region narrower than w_0 made the transverse electric
polarization mode more dominant.

Thus, making the width of the local annealing
region wider or narrower than w_0, twice the distance
from the top surface of the over-cladding to the core
center, enables the permanent effective refractive
index control of the optical waveguide with retaining
the polarization dependency. In particular, the local
annealing using at least two types of widths makes it
possible to achieve the permanent effective refractive
index control, that is, birefringence index control
with ensuring the complete independence between the
transverse electric polarization mode and transverse
magnetic polarization mode.

Since the polarization dependency of the
effective refractive index is determined by the stress
distribution caused by the local annealing, using at
least two types of local annealing with different
stress distribution principally enables the permanent
effective refractive index control or the
birefringence index control with securing the complete
independence between the transverse electric
polarization mode and the transverse magnetic
polarization mode. Accordingly, similar effect can be
produced by utilizing the difference, for example, in
the distance between the local annealing region and

the waveguide center, or in the structure such as
geometry of the local annealing region in addition to
the width of the local annealing region. Furthermore,
the stress geometry can be changed by forming a trench

5   by removing part of the cladding near the local
annealing region, and by changing its position, depth,
etc.

Since the optical path length trimming by the
local annealing is only for the purpose of fine

10 adjustment, when a delay difference (optical path
length difference) is required in the circuit design,
it is preferable to provide a fixed delay optical
circuit in advance, and to carry out the trimming in
the final stage to improve the characteristics.

15 As for the annealing means, although a method
using the thin film heater is preferable considering
the device cost, this is not essential. Any means
that can perform the local annealing of the cladding
are applicable. For example, a local annealing

20 (heating) means such as a CO_2 laser can be utilized.

In summary, the present invention is based on the
following new findings. That is, the local annealing
can permanently change the refractive index of the
optical waveguide consisting of a core and a cladding

25 because it can cause a stress to be applied on the
core because of the changes in the quality in the
heated portions. Therefore, changing the width of the

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region to be transformed by annealing (heating), or the distance or position thereof with respect to the waveguide can make the refractive index of the transverse electric polarization mode greater than, or

5 smaller than, or equal to that of the transverse magnetic polarization mode.

According to the findings above, the interferometer and its fabrication method in accordance with the present invention are

10 characterized in that the refractive index or the optical path length is adjusted by annealing the waveguide with at least two types of annealing regions having effect on the polarization.

For example, employing a combination of a first

15 annealing region, which changes the refractive index of the transverse electric polarization mode more dominantly than that of the transverse magnetic polarization mode, and a second annealing region, which equally changes the refractive index of the

20 transverse electric polarization mode and that of the transverse magnetic polarization mode, enables the phase difference of the transverse electric polarization mode to be adjusted to $\lambda/2$ and that of the transverse magnetic polarization mode to zero in a

25 single interferometer, by establishing the optical path length difference between the transverse electric polarization mode and the transverse magnetic

polarization mode at a desired value ($\lambda/2$, for example) by the first annealing region, and then by shifting the optical path length difference of the two polarization modes by the same amount.

5   On the basis of the foregoing findings, according to a first aspect of the present invention, there is provided an interferometer using an optical waveguide, which is formed by embedding a core that has a refractive index higher than that of a cladding into

10   the cladding on a substrate, the interferometer comprising: at least two types of annealing regions that are provided near the optical waveguide, wherein an optical path length of the optical waveguide is trimmed by partially changing an effective refractive

15   index of the optical waveguide by applying annealing to the annealing regions.

Here, as for the structure of the annealing regions: the annealing regions may differ in their width; at least one of the annealing regions may have

20   a width equal to or greater than 2.6 times a distance d from the core center to the top surface of the cladding, or at least one of the annealing regions may have a width equal to or less than 1.4 times the distance from the core center to the top surface of

25   the cladding; the annealing regions may differ in their distances from the optical waveguide to the annealing regions; the annealing regions may differ in

presence or absence of a slit formed in the annealing
regions in an optical waveguide direction, or in slit
width; the annealing regions may differ in presence or
absence of a trench formed by partially removing a
cladding around the optical waveguide, or in distance
from the optical waveguide to trenches, or in depth of
the trenches; the interferometer may further comprise
fixed delay means for providing delay dependent on a
polarization state; and the interferometer may
comprise at least one optical coupler and a plurality
of optical waveguides connected to the optical coupler.

The interferometer may comprise two 2×2 optical
couplers and two optical waveguides connecting the
optical couplers, wherein optical path length
difference (delay difference) between the two optical
waveguides may be trimmed by local annealing (heating)
such that it may be an odd multiple of $\lambda/2$ for a
transverse electric polarization mode and an even
multiple of $\lambda/2$ for a transverse magnetic polarization
mode, where λ is a wavelength, or that it may be an
even multiple of $\lambda/2$ for the transverse electric
polarization mode and an odd multiple of $\lambda/2$ for the
transverse magnetic polarization mode; at least one of
the two optical waveguides connecting the two 2×2
optical couplers may comprise polarization dependent
fixed delay means; and the local annealing regions may
consist of a thin film heater formed on the optical

waveguide.

As for the interferometer in which the
independent effective refractive index control is not
necessary for the transverse electric polarization
5   mode and for the transverse magnetic polarization mode,
and desired optical characteristics are achieved by
polarization independent trimming, according to a
second aspect of the present invention, there is
provided an interferometer using an optical waveguide,
10   which is formed by embedding a core that has a
refractive index higher than that of a cladding into
the cladding on a substrate, the interferometer
comprising: one type of annealing region that has a
width from 1.4 to 2.6 times a distance from the
15   optical waveguide core center to a top surface of the
cladding in a neighborhood of the optical waveguide,
wherein an optical path length of the optical
waveguide is trimmed by changing an effective
refractive index of the optical waveguide by applying
20   annealing to the annealing region.

According to a third aspect of the present
invention, there is provided an interferometer
fabrication method, wherein local annealing regions
utilize thin film heaters formed on the optical
25   waveguide.

As described above, the interferometer in
accordance with the present invention can adjust the

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birefringence index by changing the film quality of
the cladding by locally annealing it to cause the
stress change by the changing.

In addition, the interferometer may include at
5   least two types of local annealing regions with a
stress distribution inducing structure. Accordingly,
it has at least two independent trimming parameters
with different polarization dependency of the
permanent effective refractive index changes. As a
10 result, it can perform completely independent
birefringence index trimming for the transverse
electric polarization mode and for the transverse
magnetic polarization mode.

When the width of the local annealing (heating)
15 region is 1.4-2.6 times the distance from the top
surface of the over-cladding to the core center, the
change in the effective refractive index is
approximately independent of the polarization state.
Accordingly, the one type of local annealing region
20 can adjust the optical path length (phase) in a
polarization independent manner.

In particular, using the thin film heaters in the
local annealing obviates the need for high accuracy
alignment of the irradiation position at the local
25 annealing. Thus, simply supplying current to a
predetermined thin film heater is enough to achieve
the trimming, thereby enabling the trimming using a

rather simple device, which is very advantageous in putting the device in accordance with the present invention into practical use.

Moreover, applying the present invention to various types of interferometers such as a polarization beam splitter enables the interference optical path length to be adjusted for each polarization mode, thereby making it possible to achieve high optical characteristics without the phase control using the thermo-optic effect. Thus, the present invention is very advantageous in terms of the power saving of the interferometer.

The above and other objects, effects, features and advantages of the present invention will become more apparent from the following description of embodiments thereof taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A is a plane view of a conventional polarization beam splitter (PBS);

Fig. 1B is a cross-sectional view taken along the line IB-IB of Fig. 1A showing the conventional polarization beam splitter (PBS);

Fig. 1C is a cross-sectional view taken along the line IC-IC of Fig. 1A showing the conventional

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polarization beam splitter (PBS);

Fig. 2A is a plane view showing a basic configuration of the interferometer in accordance with the present invention;

5   Fig. 2B is a cross-sectional view taken along the line IIB-IIB of Fig. 2A showing the basic configuration of the interferometer in accordance with the present invention;

Fig. 3 is a characteristic diagram illustrating
10   permanent refractive index changes by local annealing;

Fig. 4A is a plane view of a polarization beam splitter (PBS) as a first embodiment in accordance with the present invention;

Fig. 4B is a cross-sectional view taken along the
15   line IVB-IVB of Fig. 4A showing the polarization beam splitter (PBS) of the first embodiment in accordance with the present invention;

Fig. 4C is a cross-sectional view taken along the line IVC-IVC of Fig. 4A showing the polarization beam
20   splitter (PBS) of the first embodiment in accordance with the present invention;

Fig. 5A is characteristic diagrams illustrating the optical path length differences of the PBS before trimming;

25   Fig. 5B is characteristic diagrams illustrating the optical path length differences of the PBS after the birefringence trimming;

Fig. 5C is characteristic diagrams illustrating the optical path length differences of the PBS after the birefringence trimming and effective refractive index trimming;

Fig. 6A is a plane view of a polarization beam splitter (PBS) as a second embodiment in accordance with the present invention;

Fig. 6B is a cross-sectional view taken along the line VIB-VIB of Fig. 6A showing the polarization beam splitter (PBS) of the second embodiment in accordance with the present invention;

Fig. 6C is a cross-sectional view taken along the line VIC-VIC of Fig. 6A showing the polarization beam splitter (PBS) of the second embodiment in accordance with the present invention;

Fig. 7A is a plane view of a polarization beam splitter (PBS) as a third embodiment in accordance with the present invention;

Fig. 7B is a cross-sectional view taken along the line VIIB-VIIB of Fig. 7A showing the polarization beam splitter (PBS) of the third embodiment in accordance with the present invention;

Fig. 8A is a plane view showing a Mach-Zehnder interferometer as a fourth embodiment in accordance with the present invention;

Fig. 8B is a plane view showing a Michelson interferometer as a fifth embodiment in accordance

with the present invention;

Fig. 8C is a plane view showing a Fabry-Perot interferometer as a sixth embodiment in accordance with the present invention;

5   Fig. 8D is a plane view showing a ring resonance filter as a seventh embodiment in accordance with the present invention;

Fig. 9A is a plane view showing a variation of the basic configuration in accordance with the present
10   invention;

Fig. 9B is a cross-sectional view taken along the line IXB-IXB of Fig. 9A showing the variation of the basic configuration in accordance with the present invention;

15   Fig. 9C is a cross-sectional view taken along the line IXC-IXC of Fig. 9A showing the variation of the basic configuration in accordance with the present invention;

Fig. 10A is a plane view showing a variation of
20   the basic configuration in accordance with the present invention;

Fig. 10B is a cross-sectional view taken along the line XB-XB of Fig. 10A showing the variation of the basic configuration in accordance with the present
25   invention;

Fig. 11A is a plane view showing a variation of the basic configuration in accordance with the present

invention;

Fig. 11B is a cross-sectional view taken along the line XIB-XIB of Fig. 11A showing the variation of the basic configuration in accordance with the present invention;

Fig. 12A is a plane view showing a variation of the basic configuration in accordance with the present invention;

Fig. 12B is a cross-sectional view taken along the line XIIB-XIIB of Fig. 12A showing the variation of the basic configuration in accordance with the present invention;

Fig. 13A is a plane view showing a variation of the basic configuration in accordance with the present invention;

Fig. 13B is a cross-sectional view taken along the line XIIIB-XIIIB of Fig. 13A showing the variation of the basic configuration in accordance with the present invention;

Fig. 13C is a cross-sectional view taken along the line XIIIC-XIIIC of Fig. 13A showing the variation of the basic configuration in accordance with the present invention;

Fig. 14A is a plane view showing a polarization independent optical switch in accordance with the present invention; and

Fig. 14B is a cross-sectional view taken along

the line XIVB-XIVB of Fig. 14A showing the
polarization independent optical switch in accordance
with the present invention.

     The embodiments in accordance with the present
invention will now be described with reference to the
accompanying drawings.
10   Figs. 2A and 2B are views showing a basic
structure of an interferometer in accordance with the
present invention. The interferometer, which is
formed as a part of the waveguide arms for
establishing the optical path length difference,
15   comprises two types of local annealing(heating)
regions with different widths as shown in Fig. 2A. In
Figs. 2A and 2B, the reference numeral 1 designates a
silicon substrate, 2 designates a waveguide core, 3
designates a cladding, 4a and 4b each designates a
20   local annealing thin film heater and 5 designates a
feeding electrode and electrode pad.
     It is assumed in Figs. 2A and 2B that the
refractive index changes by the local annealing by the
heater with a width w are δ_{TE} and δ_{TM} for respective
25   polarization modes, that the refractive index change
at the average polarization is δ_a (= (δ_{TE} + δ_{TM})/2),
and that the polarization dependency difference

between the refractive index changes is δ_p $(= \delta_{TE} - \delta_{TM})$. In this case, since the refractive index dependency difference δ_p is approximately proportional to the average refractive index change δ_a as illustrated in Fig. 3, it can be expressed as $\delta_p = C(w) \cdot \delta_a$. Here, $C(w)$ is a proportionality constant, which depends on the width of the local annealing region as shown in Fig. 3. The polarization independence C is zero ($C=0$) when $w=w_0$; less than zero ($C<0$) when $w>w_0$ at which the transverse magnetic polarization mode is dominant; and greater than zero ($C>0$) when $w<w_0$ at which the transverse magnetic polarization mode is dominant. Here, w_0 is twice the distance d from the top surface of the over-cladding to the core center. As for the waveguide having two types of local annealing regions with the widths w_1 and w_2 as shown in Fig. 2A, the total average refractive index change δ_A and the total polarization dependent refractive index difference δ_P are expressed as follows:

$$\delta_A = \delta_{a1} + \delta_{a2} \qquad (1a)$$
$$\delta_P = \delta_{p1} + \delta_{p2}$$
$$= C(w_1) \cdot \delta_{a1} + C(w_2) \cdot \delta_{a2} \qquad (1b)$$

Thus, the determinant of the equation is nonzero when $C(w_1) \neq C(w_2)$. Accordingly, the δ_{a1} and δ_{a2} that

satisfy given δ_A and δ_P are uniquely determined.
Therefore, the average refractive index change δ_A and
the polarization dependent refractive index difference
δ_P can be controlled completely independently, thereby
enabling the transverse electric polarization mode and
the transverse magnetic polarization mode to be
controlled completely independently.

In the case where the width of the local
annealing region is in a range of 1.4-2.6 times the
distance from the top surface of the over-cladding to
the core center, which nearly equals w_O ($\pm 30\%$) that
is about twice the distance, the change in the
effective refractive index is nearly independent of
the polarization state. Accordingly, only one local
annealing region is enough to trim the optical path
length (phase) in a polarization independent manner.

In the local annealing, since the refractive
index change usually takes a positive value, there is
a restriction that δ_{a1} and δ_{a2} are positive. However,
since the optical path length difference of the
interferometer is a relative value, the negative
values are allowed by increasing the optical path
length of the other path.

The present invention will now be described in
more detail using concrete embodiments. Here, the
following embodiments are assumed to employ silica-
based single mode optical waveguides formed on a

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silicon substrate because the silica-based waveguides have superior characteristics such as low loss, long-term stability and good affinity for communication silica fibers as described at the top of the specification. However, it is obvious the present invention is applicable to all the materials that allow the stress control of the cladding by the local annealing. For example, they can be combined with other materials such as a quartz substrate or sapphire substrate as a substrate material, or with a composite glass, polymer material or lithium niobate as an optical waveguide.

In the following description, the components with the same functions as those of Figs. 2A and 2B are designated by the same reference numerals to omit unnecessary duplication of the description.

[EMBODIMENT 1: PBS1]

Figs. 4A-4C shows a configuration of a polarization beam splitter (PBS) of a first embodiment used as an interferometer. Here, Fig. 4A is a plane view, Fig. 4B is a cross-sectional view taken along the line IVB-IVB of Fig. 4A, and Fig. 4C is a cross-sectional view taken along the line IVC-IVC of Fig. 4A. In Figs. 4A-4C, the reference numeral 8 designates a stress releasing groove (λ /2 polarization dependent delay means), reference numerals 41a and 41b each

designate a local annealing thin film heater ($w \fallingdotseq w_o$),
42a and 42b each designate a local annealing thin film
heater ($w > w_o$), and 43a and 43b each designate a
local annealing thin film heater ($w < w_o$).

5   The PBS comprises, on an MZI that is composed of
two 50% (3dB) optical couplers 7 and 7, two waveguide
arms 2a and 2b linking the two couplers, and
input/output waveguides connecting input/output ports
with the couplers, the $\lambda/2$ polarization dependent

10   delay means 8 for providing the MZI with the optical
path length change of about $\lambda/2$ (λ is a wavelength)
depending on the polarization state of the transverse
electric polarization mode and the transverse magnetic
polarization mode; and the thin film heaters 41a, 41b,

15   42a, 42b, 43a and 43b that are mounted on both sides
of the waveguide arms and operate as the local
annealing (heating) means with three types of widths.

       The PBS of the present embodiment employs
directional couplers formed by placing the two

20   waveguides in close proximity of about a few
micrometers as the 3dB couplers 7 and 7. This is
because the directional couplers have a lower
insertion loss than other components. However, the
3dB couplers are not limited to this configuration.

25   For example, it is possible to employ multi-mode
interference couplers (MMIs) utilizing multi-mode
waveguides, or wavelength insensitive couplers (WINC)

formed by connecting these couplers in cascade.

The PBS of the present embodiment employs a structure that provides the stress releasing grooves 8 on both sides of one of the waveguide arms as the $\lambda/2$ polarization dependent delay means (see, Japanese Patent Application Laying-open No.63-182608 (1988)). This is because the structure using the stress releasing grooves 8 has a low insertion loss. However, the $\lambda/2$ polarization dependent delay means is not limited to this structure. Other configurations are also allowed such as inserting a half wave-plate into one of the waveguide arms with the principle axis forming zero degree or 90 degrees with the arm. In addition, although the stress releasing grooves 8 are formed at the upper waveguide arm (at the sides of the waveguide core 2a) in the present PBS to establish the $\lambda/2$ polarization dependent delay difference, since the delay difference is relative, they can be formed on the lower waveguide arm (at the sides of the waveguide core 2b), or at both sides of them with the grooves different in length on the upper and lower sides to implement the $\lambda/2$ polarization dependent delay difference.

Furthermore, since the optical path length of each waveguide arm is determined as a line integral of the effective refractive index on the waveguide, the $\lambda/2$ polarization dependent delay means 8 and the

local annealing means 41a, 41b, 42a, 42b, 43a and 43b with the three types of widths can be arranged in any order on the waveguide arms.

The PBS of the present embodiment was formed on the one millimeter thick silicon substrate 1 with a diameter of four inches by using a conventional technique. The silica-based waveguides were formed by a combination of the reactive ion etching technique with the deposition technique of a silica-based glass film based on the flame hydrolysis reaction deposition technique that utilized the hydrolysis reaction of the material gases such as $SiCl_4$ or $GeCl_4$, and the local annealing (heating) thin film heaters 41a, 41b, 42a, 42b, 43a and 43b were formed by the vacuum deposition and etching, followed by forming the stress releasing grooves 8 by the reactive ion etching. The cross section of the cores is 6 μm $\times$ 6 μm square. The cores 2a and 2b are surrounded by the cladding 3 of about 40 μm thick, and the core center is located at a distance of 15 μm from the top surface of the cladding. The relative refractive index difference between the cores 2a and 2b and the cladding 3 is 0.75%.

The arm length of the two waveguide arms was about 20 mm with the arm length difference being zero, and the arm spacing was 1 mm. Each of the stress releasing grooves 8 was about 1.9 mm long in the waveguide direction and 50 μm wide. The distance from

the waveguide center to each stress releasing groove 8
was 25 μm. The three types of the thin film heaters
have a width of 15 μm ($<$ w_o) (43a, 43b), 30 μm ($\doteqdot$
w_o) (41a, 41b) and 60 μm ($>w_o$) (42a, 42b) with a
5   length of 5 mm, where w_o is about twice the distance
from the top surface of the over-cladding to the core
center.

The wafer was diced and fixed to a ceramic
substrate. The input/output ports 11a, 11b, 12a and
10   12b were each connected to a single mode fiber, and
the thin film heaters 41a, 41b, 42a, 42b, 43a and 43b
were each connected with a feeding lead via the
feeding electrode pad 5, thereby completing the PBS
module.

15   The optical circuit fabricated through the
foregoing process has a strong compressive stress in
the direction within the surface because of the
thermal expansion difference between the silicon
substrate and the silica-based glass. Accordingly,
20   the waveguides have a waveguide birefringence of $4\times$
10^{-4}, with the transverse magnetic polarization mode
having a slightly higher refractive index than the
transverse electric polarization mode. On the other
hand, since the stress is released by the stress
25   releasing grooves 8, the waveguide birefringence at
that portion is about zero. Therefore, the presence
and absence of the 1.9 mm long stress releasing

grooves 8 in the two waveguide arms cause the polarization dependency of about $\lambda/2$ in the optical path length difference. As a result, the present circuit constitutes the MZI with the optical path

5 length difference of about zero in the transverse electric polarization mode, and the MZI with the optical path length difference of about $\lambda/2$ in the transverse magnetic polarization mode. Thus, according to the well-known interference principle, as

10 for the light launched into the input port (11b), the light in the transverse electric polarization mode is led to the cross port (12a), and the light in the transverse magnetic polarization mode is led to the bar port (12b).

15 The term "about" is used in the foregoing description because the optical circuit fabricated has some fabrication error, and hence the designed optical path length difference usually deviates slightly. Thus, to achieve a satisfactory extinction ratio, it

20 is very important to correct the error accurately. The correction method, the subject matter of the present invention, will now be described in detail.

Fig. 5A illustrates the characteristics of the present PBS. The characteristics were measured using

25 the thin film heaters with the width of 30 μm as a thermo-optic phase shifter. The horizontal axis represents the driving power supplied to the thin film

heater. In Fig. 5A, the right-hand side represents
the case where the upper thin film heater 41a was fed,
whereas the left-hand side represents the case where
the lower thin film heater 41b was fed. As

5   illustrated in this figure, when the driving power is
zero, the light in the transverse electric
polarization mode leaks into the bar port 12b, and the
light in the transverse magnetic polarization mode
leaks into the cross port 12a, resulting in only an

10   insufficient extinction ratio. In addition, it is
found from the driving characteristics that to achieve
a sufficient extinction ratio, the effective
refractive index of the upper arm must be increased to
lengthen its optical path length to some extent in the

15   transverse electric polarization mode, and the
effective refractive index of the lower arm must be
increased to some extent to lengthen its optical path
length in the transverse magnetic polarization mode.

     As illustrated in Fig. 3, the local annealing by

20   the thin film heaters with various widths enables the
control of the effective refractive index.
Specifically, the thin film heater with the width of
30 μm can achieve the polarization independence (C $\fallingdotseq$
0 in expression (1b)); the thin film heater with the

25   width of 15 μm can increase the effective refractive
index with about 25% dominance (C $\fallingdotseq$ 0.25 in expression
(1b)) of the transverse electric polarization mode;

and the thin film heater with the width of 60 μm can
increase the effective refractive index with about 25%
dominance (C $\fallingdotseq$ -0.25 in expression (1b)) of the
transverse magnetic polarization mode.

This trimming was carried out in the two steps:
(1) trimming the difference ΔL_P (= ΔL_{TE} - ΔL_{TM}) to
$\lambda/2$, where ΔL_{TE} was the optical path length
difference (= upper arm - lower arm) between the
waveguide arms in the transverse electric polarization
mode, and ΔL_{TM} was the optical path length difference
between the two arms in the transverse magnetic
polarization mode; and (2) trimming to ΔL_{TE} = 0 (and
hence, ΔL_{TM} = -$\lambda/2$).

At the end of the fabrication of the circuit
whose characteristics are illustrated in Fig. 5A, the
ΔL_P is about 0.8·$\lambda/2$. As described above, the local
annealing using the 15 μm wide thin film heater 43a of
the upper arm or the 60 μm wide thin film heater 42b
of the lower arm will both increase the ΔL_P. The
optical path length differences ΔL_{TE} and ΔL_{TM} in
both the polarization will increase when using the
thin film heater 43a of the upper arm, and decrease
when using the thin film heater 42b of the lower arm.
In view of this, the trimming was performed by using
both the thin film heaters 43a and 42b so that the
ΔL_{TE} and ΔL_{TM} do not deviate greatly to one
direction during the trimming of the ΔL_P. More

specifically, the thin film heater 43a was supplied
with the power of 7.5 W, and the thin film heater 42b
was supplied with the power of 10W, each of which was
supplied for a few seconds, at several times. Thus,
5   the local annealing was carried out with observing the
changes in the ΔL_{TE} and ΔL_{TM} at each step. As a
result, the local annealing, which was applied to the
thin film heater 43a for 20 seconds in total, and to
the thin film heater 42b for 100 seconds in total, was
10 able to establish the permanent phase characteristics
of the PBS at $\Delta L_P = \lambda/2$ as illustrated in Fig. 5B.

Although the ΔL_P was set at $\lambda/2$, the $\Delta L_{TE} =$
$0.07 \cdot \lambda/2$. Accordingly, the local annealing was
carried out using the 30 μm wide thin film heater 41b
15 of the lower arm to trim the ΔL_{TE} to zero. As
described above, since the local annealing using the
30 μm wide thin film heater can increase the
refractive index in an approximately polarization
independent manner, the trimming of the ΔL_{TE} can be
20 implemented with maintaining the $\Delta L_P = \lambda/2$. More
specifically, the local annealing was performed by
supplying the thin film heater 41b with the power of 6
W for ten seconds. As a result, the phase
characteristics of the PBS as illustrated in Fig. 5C
25 were obtained. Thus, the $\Delta L_{TE} = 0$ (that is, $\Delta L_{TM} =$
$-\lambda/2$) was achieved with maintaining the relationship
$\Delta L_P = \lambda/2$.

As a result, the following satisfactory conditions were established even at the zero driving power: the insertion loss was about 1dB; and the polarization extinction ratio was about 30 dB in both the transverse electric polarization mode and transverse magnetic polarization mode.

In this trimming, although the local annealing was carried out by dividing the annealing time and by controlling the total annealing time according to the changes in the ΔL_{TE} and ΔL_{TM} for accuracy, the annealing can be performed at one time when some error is accepted.

In addition, although the trimming was carried out through two distinct steps (1) and (2), the former trimming the polarization dependent phase differences and the latter trimming the phase difference in a polarization independent manner, a slight deviation of the ΔL_P could remain after the step (2) in some samples. In such a case, the trimming can be repeated from the step (1).

Although the trimming carried out both the steps (1) and (2), the former trimming the polarization dependent phase differences, and the latter trimming the phase difference in a polarization independence manner, since the latter can be achieved using the thermo-optic effect, for example, it is possible to perform only the step (1) with omitting the step (2),

followed by the trimming using a thermo-optic phase
shifter. In this case, however, since the thermo-
optic phase shifter must be continuously supplied with
the driving power, the trimming using both the steps
5 (1) and (2) is preferable from the viewpoint of power
saving.

The trimming did not use the thin film heaters
43b and 42a. This is because the polarization
dependency difference $\Delta L_{P(o)}$ in the optical path
10 length difference in the initial state was less than
the finally set polarization dependency difference
$\Delta L_{P(f)}$ (which is equal to $\lambda/2$ in this case).
Therefore, designing the $\lambda/2$ polarization dependent
delay means 8 such that the relationship $\Delta L_{P(o)} <$
15 $\Delta L_{P(f)}$ always holds considering the fabrication
error enables the thin film heaters 43b and 42a to be
omitted, thereby reducing the circuit size. On the
contrary, designing such that the relationship $\Delta L_{P(o)}$
$> \Delta L_{P(f)}$ holds enables the thin film heaters 43a and
20 42b to be omitted.

In addition, the ΔL_P can be increased by the
local annealing using the 15 μm wide thin film heater
43a of the upper arm or the 60 μm wide thin film
heater 42b of the lower arm. Furthermore, the optical
25 path length differences ΔL_{TE} and ΔL_{TM} of the
individual polarization can be increased by the local
annealing using the thin film heater 43a, and

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decreased by that using the thin film heater 42b. Accordingly, sharing the amount of the local annealing between the upper arm and lower arm makes it possible to trim the ΔL_P to $\lambda/2$, and the ΔL_{TE} to zero. Thus, the thin film heaters 41a and 41b can be omitted in this case, thereby being able to further reduce the circuit size. This will be described in more detail in the embodiment 2.

In the PBS of the present embodiment 1, although the optical path length difference between the waveguide arms was set zero to the transverse electric polarization mode, and $\lambda/2$ to the transverse magnetic polarization mode, this is not essential. Principally, the optical path length difference between the waveguide arms can be set at an integer multiple of $\lambda/2$ in the transverse electric polarization mode, and at the optical path length difference in the transverse electric polarization mode plus or minus an odd multiple of $\lambda/2$ in the transverse magnetic polarization mode to enable the PBS to operate. However, since an increasing optical path length difference in the MZI generally enhances the wavelength dependency, it will limit the wavelength band that can provide a sufficient extinction ratio. Accordingly, it is preferable that the optical path length difference be small.

[EMBODIMENT 2: PBS2]

Figs. 6A-6C show a configuration of a polarization beam splitter (PBS) in a second embodiment used as an interferometer. Fig. 6A is a plane view, Fig. 6B is a cross-sectional view taken along the line VIB-VIB of Fig. 6A, and Fig. 6C is a cross-sectional view taken along the line VIC-VIC of Fig. 6A. Although the configuration is similar to that of the PBS of the first embodiment, it differs in that the number and types of the thin film heaters are reduced. Specifically, it comprises only two types of thin film heaters, a 15 μm (< w_o) wide thin film heater 43 and a 60 μm (> w_o) wide thin film heater 42, each assigned to one of the arms as a local annealing(heating) means. In addition, the stress releasing grooves 8 as a $\lambda/2$ polarization dependent delay means are designed slightly shorter at 1.7 mm so that the polarization dependency difference ΔL_P of the optical path length difference between the waveguide arms becomes always less than $\lambda/2$ (that is, $L_{P(o)} < \Delta L_{P(f)}$).

The optical circuit of the second embodiment is formed to a module by the same fabrication method as the first embodiment.

Estimating the characteristics using the thin film heaters 43 and 42 as in the first embodiment gives the values $\Delta L_{TE(o)} = -0.1 \cdot \lambda/2$, $\Delta L_{TM(o)} = -$

$0.8 \cdot \lambda /2$, and $\triangle L_{P(O)} = 0.7 \cdot \lambda /2$. Accordingly, the trimming amounts needed for the individual polarization are δL_{TE} (= $\triangle L_{TE(E)}$ - $\triangle L_{TE(O)}$) = $0.1 \cdot \lambda /2$, and δL_{TM} (= $\triangle L_{TM(E)}$ - $\triangle L_{TM(O)}$) = $-0.2 \cdot \lambda /2$.

5   Therefore, the trimming amount of the polarization dependency difference and the trimming amount of the optical path length of the polarization independence are δL_P = $0.3 \cdot \lambda /2$, and δL_a = $-0.05 \cdot \lambda /2$, respectively.

Since both the thin film heaters 43 and 42 have a

10   length l = 5 mm, the change amount δL_P of the polarization dependency difference and the optical path length change amount δL_a of the polarization independence by the local annealing are given by the following expressions:

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$$\delta L_a = 1 \cdot (\delta_{a1} - \delta_{a2}) \tag{2a}$$
$$\delta L_P = 1 \cdot (\delta_{p1} - \delta_{p2}) = 1 \cdot (C_1 \cdot \delta_{a1} - C_2 \cdot \delta_{a2}) \tag{2b}$$

where δ_{a1} and δ_{a2} are refractive index changes of the

20   polarization independence, and δ_{p1} and δ_{p2} are polarization dependency differences of the refractive index changes due to the local annealing by the thin film heaters 43 and 42. As described before, since C_1 = 0.25 in the 15 μm wide thin film heater 43, and C_2

25   = -0.25 in the 60 μm wide thin film heater 42, solving the simultaneous equations gives δ_{a1} = 8.9×10^{-5} and δ_{a2} = 9.7×10^{-5}.

To implement the refractive index changes, the
thin film heater 43 was supplied with the power of 7.5
W for 28 seconds, and the thin film heater 42 with the
power of 12 W for 67 seconds to achieve the local
annealing. As a result, the L_{TE} = 0 and ΔL_{TM} = $-\lambda/2$
were established permanently. Thus, the following
satisfactory conditions were established even at the
zero driving power: the insertion loss was about 1dB;
and the polarization extinction ratio was about 30 dB
in both the transverse electric polarization mode and
transverse magnetic polarization mode.

[EMBODIMENT 3: PBS3]

Figs. 7A and 7B shows a configuration of a
polarization beam splitter (PBS) used as an
interferometer of a third embodiment. Fig. 7A is a
plane view; and Fig. 7B is a cross-sectional view
taken along the line VIIB-VIIB of Fig. 7A. The
configuration is similar to the PBS of the second
embodiment except that it does not comprise the $\lambda/2$
polarization dependent delay means, but comprises a
plurality of thin film heaters 43a-43d with the same
structure and thin film heaters 42a-42d with the same
structure as the local annealing(heating) means. In
addition, the PBS has the optical path length
difference of $\lambda/2$ with making the upper waveguide
slightly longer in order to level out the amounts of

the heating power as will be described later. The
total length of the thin film heaters, that is, the
total length of the local annealing regions, is
increased from that of the second embodiment by 20 mm
considering the trimming amount in this embodiment.
In addition, the spacing between the waveguide arms is
set at 250 μm.

The PBS of the present embodiment is formed into
a module by the same fabrication method as the first
embodiment.

Measuring the characteristics using the thin film
heaters 43a and 42a as in the first embodiment gave
the values $\Delta L_{TE(o)} = \lambda/2$, $\Delta L_{TM(o)} = \lambda/2$, and
$\Delta L_{P(o)} = 0$. The PBS of the present embodiment
comprises four thin film heaters for each waveguide
arm, with the total length thereof $l = 20$ mm.
Accordingly, the calculation as in the second
embodiment gave the desired refractive index changes
of $\delta_{a1} = 9.7 \times 10^{-5}$ and $\delta_{a2} = 5.8 \times 10^{-5}$.

To bring about the refractive index changes, the
local annealing was carried out by sequentially
supplying the 15 μm ($< w_o$) long thin film heaters
43a-43d with the power of 7.5 W for 50 seconds, and
the 60 μm ($> w_o$) long thin film heaters 42a-42d with
the power of 10W for 100 seconds. As a result, the
$L_{TE} = 0$ and $\Delta L_{TM} = -\lambda/2$ were established permanently.
Thus, the following satisfactory conditions were

established even at the zero driving power: the insertion loss was about 1dB; and the polarization extinction ratio was about 30 dB in both the transverse electric polarization mode and transverse

5 magnetic polarization mode.

When heating by the same power, the local annealing using a narrower heater usually has a greater heating density per unit area than the local annealing using a wider heater, thereby causing a

10 larger refractive index change as illustrated in Fig. 3. In view of this, the PBS of the present embodiment established the optical path length difference of $\lambda/2$ in the MZI so that the refractive index change δ_{a2} by the 60 μm wide thin film heaters 42a-42d became

15 smaller than the refractive index change δ_{a1} by the 15 μm wide thin film heaters 43a-43d, thereby leveling out the heating power amounts.

In the present embodiment, although the local annealing was performed for the four thin film heaters

20 43a-43d and the four thin film heaters 42a-42d separately, this is not essential. It can be carried out simultaneously. Alternatively at least one of the two sets, where one set consists of the four thin film heaters 43a-43d of the upper waveguide arm and the

25 other set consists of the four thin film heaters 42a-42d of the lower waveguide arm, can be made one type of thin film heater of 20 mm long, without dividing

into four heaters. In this case, however, since the
thin film heater of the lower waveguide arm in
particular requires the power of no less than 40W, a
powerful cooling system for the substrate is necessary.

5   Furthermore, although the PBS of the present
embodiment divides the thin film heaters with the
total length of 20 mm into four equal parts, this is
not essential. For example, they can be divided into
unequal parts, such as 15 mm and 5 mm so that the 15
10 mm long heater is used for rough trimming, and the 5
mm long heater is used for fine trimming.

[EMBODIMENTS 4-7: Applications to Other
Interferometers]
15   Figs. 8A-8D show embodiments as applications to
various interferometers.
       Fig. 8A shows an example of a Mach-Zehnder
interferometer (transmission Interferometer) that has
a desired optical path length difference between the
20 waveguide arms between the couplers.
       Fig. 8B shows an example of a Michelson
interferometer (reflection interferometer) that
comprises reflectors 9 at the end of the optical paths
branching from the coupler, and has a desired optical
25 path length difference between the round-trip optical
path length difference between the coupler and the
reflector 9.

Fig. 8C shows an example of a Fabry-Perot
interferometer (round-trip interferometer) that
provides the waveguide with a desired round-trip
optical path length (resonance length), and comprises
5   half mirrors 10 with the reflectivity of about 99%.
The reference numerals 11 and 12 each designate an
input/output port.

Fig. 8D shows an example of a ring resonance
filter that implements a desired optical path length
10   (resonance length) by a ring circuit 2c.

All the foregoing interferometers and filters
implement a desired wavelength (frequency)
transmission characteristics by establishing the
optical path length difference or resonance length at
15   a desired length ΔL (= effective refractive index $\times$
waveguide length difference). However, since the
effective refractive index of the waveguide is
slightly higher in the transverse magnetic
polarization mode than in the transverse electric
20   polarization mode as described before in the
embodiment 1, the optical path length difference and
the resonance length are longer in the transverse
magnetic polarization mode than in the transverse
electric polarization mode.

25   These interferometers are characterized by
exhibiting nearly the same wavelength characteristics
in the neighborhood of the target wavelength λ even at

the optical path length difference or the resonance
length of $\Delta L_1 = \Delta L$ or $\Delta L_2 = \Delta L + m \cdot \lambda$, where m is an
integer. Accordingly, if the optical path length
difference between the transverse magnetic
5   polarization mode and the transverse electric
polarization mode can be adjusted to $m \cdot \lambda$, the
polarization dependency of the wavelength transmission
characteristics is eliminated apparently. Thus, it is
enough to adjust the optical path length difference
10   between the transverse magnetic polarization mode and
the transverse electric polarization mode to $m \cdot \lambda$ by
the method of the foregoing embodiments, and to adjust
the ΔL in the transverse electric polarization mode
(or the transverse magnetic polarization mode) to a
15   desired value. In this case, the value m is
preferably set as close to zero as possible because
the wavelength region that exhibits nearly the same
characteristics becomes narrower with an increase in
$|m|$ in each polarization.

20   In practice, desired characteristics were
achieved in which the polarization dependency of the
wavelength transmission characteristics were
eliminated apparently by the adjustment in these
interferometers.

25   In the foregoing embodiments, the present
invention is applied to rather simple optical circuits.
However, the present invention is not limited to these

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circuits. For example, it is obvious that the present
invention is applicable to a lattice type filter with
a plurality of Mach-Zehnder interferometers connected
in cascade, and to an arrayed waveguide grating, one
5 of multiple beam interferometers.

The foregoing embodiments utilize the difference
in the width of the local annealing regions as a means
for implementing the two or more types of local
annealing with different stress distribution. However,
10 a method of bringing about the different stress
portions is not limited to this method.

For example, the transverse electric polarization
mode and the transverse magnetic polarization mode can
be controlled independently by partially varying the
15 over-cladding depth as d_1 and d_2 with maintaining the
width w at a fixed value as shown in Figs. 9A-9C.
This is because the polarization characteristic is
determined not only by the width w of the local
annealing(heating) region, but also by the distance d
20 from the top surface of the over-cladding to the core
center. The independent control was confirmed by a
device actually fabricated. In Figs. 9A-9C, the
reference numeral 21 designates a pit for trimming the
depth of the cladding.

25 Alternatively, the transverse electric
polarization mode and the transverse magnetic
polarization mode can be controlled independently as

in the foregoing embodiments by the following methods
because they can bring about the polarization
dependency in the effective refractive index change.
A first structure: as shown in Figs. 10A and 10B, the
local annealing region is displaced from the position
immediately above the waveguide (the thin film heater
4a is located immediately above the waveguide, and the
thin film heater 4b is displaced from the waveguide by
an amount s). A second structure: as shown in Figs.
11A and 11B, the local annealing regions are provided
with slits of different widths g_1 and g_2. A third
structure: as shown in Figs. 12A and 12B, the local
annealing regions are divided into a plurality of
stripes with different density (the thin film heater
4a has a low density and the thin film heater 4a has a
high density). A fourth structure: as shown in Figs.
13A-13C, trench structures (stress distribution
trimming grooves 22a and 22b) are provided by removing
the cladding from around the local annealing regions
with varying the position and depth of the grooves
(the position CW_1 of the stress distribution trimming
groove 22a is close to the thin film heater 4a, and
the position CW_2 of the stress distribution trimming
groove 22b is distant from the thin film heater 4b).

Furthermore, although the thin film heaters
formed on the cladding are used as the local annealing
(heating) means, this is not essential. For example,

a method of locally annealing (heating) the cladding
by irradiating a CO_2 laser beam can achieve the same
effect.

5 [EMBODIMENT 8: Polarization Independent Optical
Switch]

Figs. 14A and 14B show an optical switch used as
an interferometer that can obviate the need for
controlling the effective refractive index
10 independently for the transverse electric polarization
mode and transverse magnetic polarization mode, and
that can achieve desired optical characteristics by
trimming it in a polarization independent manner. Fig.
14A is a plane view, and Fig. 14B is a cross-sectional
15 view taken along the line XIVB-XIVB of Fig. 14A.
Although the configuration of the optical switch is
similar to the PBS of the third embodiment, it differs
in comprising two thin film heaters 44a and 44b with
the same structure as a local annealing means.

20 The thin film heaters 44a and 44b, each of which
is 30 μm wide ($\fallingdotseq$ W_O: about twice the distance from
the top surface of the over-cladding to the core
center) and 5 mm long, are each disposed on one of the
two waveguide arms that are spaced 200 μm and have the
25 arm length of about 15 mm each.

The optical switch of the present embodiment is
formed into a module by the same method as that of the

first embodiment. The input/output ports 11a, 11b,
12a and 12b are each connected to a single mode fiber,
and the thin film heaters 44a and 44b are each
connected to feeding leads via feeding electrodes and
electrode pads 5.

Since the optical path length difference between
the waveguide arms is designed to be zero in both the
transverse electric polarization mode and the
transverse magnetic polarization mode in the optical
switch, the light launched into the input port, the
input/output port 11b, is guided to the cross port,
the input/output port 12a (OFF state).

When the waveguide arms are provided with a $\lambda/2$
phase difference by the thermo-optic effect caused by
supplying current to the thin film heaters 44a and 44b,
the light launched into the input port, the
input/output ports 11b, is guided to the bar port, the
input/output port 12b, thereby operating as a switch
(ON state).

Actual measurement of the optical path length
deviation by using the thin film heaters 44a and 44b
as thermo-optic phase shifters shows that the optical
path length difference $\Delta L_{(o)} = -0.1 \cdot \lambda/2$. Therefore,
the refractive index change required by the 5 mm long
local annealing regions is 1.6×10^{-5}.

To achieve the refractive index change, the local
annealing was performed by supplying the thin film

heater 44b with the power of 6W several times, each for a few seconds, with observing the changes of the ΔL each time.

As a result, supplying the power for the total of
5   14 second enabled the condition $\Delta L = 0$ to be established permanently in both the transverse electric polarization mode and transverse magnetic polarization mode. Thus, the satisfactory characteristics were achieved with the insertion loss
10   of about 1dB and the polarization extinction ratio of about 30dB without applying fine adjusting bias power in the OFF state in each polarization state.

In this trimming, although the local annealing was carried out by dividing the annealing time and by
15   controlling the total annealing (heating) time according to the changes in the ΔL for accuracy, the annealing can be performed at one time when some error is accepted.

Furthermore, although the thin film heaters
20   formed on the cladding are used as the local annealing (heating) means, this is not essential. For example, a method of locally annealing (heating) the cladding by irradiating a CO_2 laser beam can achieve a similar effect.

25   The present invention has been described in detail with respect to preferred embodiments, and it will now be apparent from the foregoing to those

skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and it is the intention, therefore, in the appended claims to cover all such changes and modifications as fall within the true spirit of the invention.